

SUMMARY REPORT

Principal Investigator: David J. Stevenson
California Institute of Technology
Division of Geological and Planetary Sciences MC 150-21
Pasadena, CA 91125
Email: djs@gps.caltech.edu

Title: Planetary Origin Evolution and Structure
Grant No. NAG5-10189

Major Research Activities

This wide-ranging grant supported theoretical modeling on many aspects of the formation, evolution and structure of planets and satellites. Many topics were studied during this grant period, including the evolution of icy bodies; the origin of magnetic fields in Ganymede; the thermal histories of terrestrial planets; the nature of flow inside giant planets (especially the coupling to the magnetic field) and the dynamics of silicate/iron mixing during giant impacts and terrestrial planet core formation. Many of these activities are ongoing and have not reached completion. This is the nature of this kind of research.

Major research Accomplishments

(1) *Dynamo Generation in Ganymede*

In this work (done primarily with Zhiming Kuang when he was a graduate student), we sought an explanation for the presence of a dynamo in Ganymede. This is a surprising property of a small body, given the absence of a dynamo in current Mars and the smallness or absence of a dynamo in Mercury. In the absence of any apparent alternative, we assumed that the dynamo is convective (i.e., arises from thermal and/or compositional convection in a metallic iron alloy core. There are four issues here: (1) Will Ganymede have such a core? (2) Will the core be liquid? (3) Will the core convect? (4) Is there enough energy to sustain a dynamo (core fields \sim a Gauss)? On the first question, the answer is that a core is likely based solely on radiogenic heating of a primordial rock/iron "core" that separates from the water ice component early in solar system history. This does of course assume sufficient reduced iron (i.e., correct range of oxygen fugacity). Unlike, terrestrial planets, where accretion al heating is probably the cause of core formation, radiogenic is needed and it will probably not melt the silicate component. Therefore, one needs a low melting point alloy, presumably because of the presence of sulfur. Moreover, the separation of iron from silicates may be imperfect because of the tendency of iron to form quasi-spherical inclusions rather than an interconnected network of melt. (2) The core will remain at least partially liquid through to present day for any reasonable sulfur content. (3) The presence of convection is difficult to predict with certainty but is aided by high sulfur content and might also benefit from the presence of potassium-40. Unlike terrestrial bodies, the high sulfur content and low pressures may

aloe operation on the sulfur-rich side of the eutectic composition. (4) Given that the conditions for convection are satisfied, there is enough energy to support a field of a few Gauss. However, the energy budget is severely constrained relative to that usually assumed for Earth, suggesting that the field is particularly simple. Unfortunately, there is insufficient known about the criteria for dynamo generation to go further with a precise prediction. The absence of a dynamo in Titan is a puzzle in this picture.

(2) Coupling of Magnetic Field to Zonal Flows in Giant Planets

In this ongoing effort (primarily with graduate student JunJun Liu), we attempt to answer the following question: Is a deep-seated zonal flow consistent with the presence of substantial coupling to a magnetic field. In the "old" picture put forward by Busse, geostrophic flow external to the core of Jupiter could be sustained as part of the thermal convection, perhaps driven by Reynolds stresses. Both the generation and dissipation of this flow is presumed to be small, so the flow can be of large amplitude (e.g., tens of meters/sec) relative to the expected convective motions (cm/sec or less). The problem with this picture is that the electrical conductivity of hydrogen can allow the magnetic field to couple to large zonal flows even at 90 or 95% of the planet radius, because a large magnetic Reynolds number can arise for even very low conductivity. Our incomplete analysis suggests that there are indeed strong constraints on the flow arising from the magnetic field, but we are not yet able to decide if the zonal flow is confined to only the outermost regions of the planet.

(3) Convection and Oceans in Icy Satellites

This work has two aspects: One is concerned with the role of ammonia in enhancing the presence of oceans. This leads to the prediction that bodies such as Triton and Pluto can be expected to have oceans. The other aspect, with Emma Rainey, focuses on the likely non-Newtonian aspect of the water ice rheology resulting from the fact that the so-called Newtonian viscosity is grain-size dependent and the grain size in turn depends on stress. We find that this enlarges the size range for which bodies are expected to have oceans, increasing the likelihood that the Galilean satellites (e.g., Ganymede) would have an ocean, even without the presence of antifreeze such as ammonia.

(4) Mixing during Giant Impacts

In numerical simulations by Canup and others, giant impacts lead to some break-up of the iron cores of the impacting bodies, but the resulting liquid "debris" is still in large blobs, typically hundreds of kilometers in extent. In calculations by Tais Dahl and the PI, we find that Rayleigh-Taylor instabilities do not fully emulsify the liquid iron and silicate. This means that there is some "memory" of previous core forming events in the outcome. In other words, Earth core formation is not merely a property of Earth itself but has a timing and thermodynamic state that is partly due to previous, much earlier and lower energy core formation events in precursor bodies. This has important implications for the interpretation of the Hf-W time scale and the compositions of the cores of terrestrial planets.

(5) *Miscellaneous Topic and Review Activities*

The PI has written a number of reviews concerning the nature of planetary magnetic fields, the interior structures and formation scenarios of giant planets, the nature of thermal histories of terrestrial planets and provocative ideas about extrasolar planets (the concept of planetary diversity).

Collaborators and Students:

Work under this grant has involved Ph.D. student Junjun Liu (supported by this grant), Zhiming Kuang, Tais Dahl (supported by this grant for short visits only; he is a masters student at University of Copenhagen) and Emma Rainey (supported only partially by this grant; most support from a DOE Fellowship).

Papers Published for the Period 2002-2005

Stevenson, Introduction to Planetary Interiors. In "High Pressure Phenomena," Volume 147, International School of Physics Enrico Fermi, Edited by: G.L. Chiarotti, M. Bernasconi, L. Ulivi and R.J. Hemley. IOS Press, Amsterdam, 587-606, 2002.

Stevenson, David J. Planetary magnetic fields. *Earth and Planetary Science Letters*, **208**, 1-11, 2003.

Stevenson, David J. Styles of Mantle Convection and their Influence on Planetary Evolution. *Comptes Rendues de L'Academie des Sciences*, **335**, 99-111, 2003.

Kono, Masaru and Stevenson, David J. Dynamo Processes and Magnetic Field of the Earth and Planets. *J. Seismo. Soc. Japan* **56** 311-325, 2003. [In Japanese].

Stevenson, David J. Planetary Diversity. *Physics Today* pp43-48, April, 2004.

Stevenson, D. J. Formation of Giant Planets. *The Search for other Worlds, Fourteenth Astrophysics conference*, ed. S. S. Holt and D. Deming, publ. American Institute of Physics (N. Y.) Conference Proceedings No. 713, pp 133-141, 2004.

Guillot, T., Stevenson, D. J. Hubbard, W. B. and Saumon, D. The Interior of Jupiter. Chapter 3 in *Jupiter* (ed. F. Bagenal et al), Cambridge University Press, 2004. pp 35-57.

Stevenson, David J. Volcanoes on Quaoar? *Nature* **432** 681-682, December 2004.

Subject Inventions: None